Additive manufacturing of geopolymer-stones to replicate natural sandstones with low availability

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HIGHLIGHTS

- Highlight 1 (development of a geopolymer fine mortar for additive manufacturing with high durability).
- Highlight 2 (natural sandstones with low availability can be replicate)
- Highlight 3 (complicated structures can be easily produced)

Key words: Additive Manufacturing, Geopolymer, Metakaolin, Sandstone replicas

INTRODUCTION

Additive manufacturing with plastics, metals, ceramics and building materials such as concrete is opening more and more areas of application and has achieved a high level of public awareness. The driving force in construction materials industry to establish additive manufacturing, is to increase productivity [1]. Three advantages of additive manufacturing are worth highlighting: Additive processes are material-efficient and resource-saving. To produce a component, only the material that is contained in the component is consumed. Thus, no significant waste is produced during manufacturing. In addition, additive manufacturing offers a maximum in geometric freedom. Shaping is not limited by a necessary demold ability. This means that almost any geometries can be created [2, 3]. Extrusion-based 3D printing is the most popular form of additive manufacturing in construction industry. The material is extruded through a nozzle and applied layer by layer to form an object [1, 2, 4]. Portland cement is usually used as binder for additively manufactured concrete components. However, the binder content is higher than for conventionally molded components [5]. Due to the high CO_2 emissions associated with the production of cement, attempts have been made to replace Portland cement with more environmentally friendly geopolymers [6, 7, 8] in additive manufacturing. In recent years, research has also begun into the potential applications of additive manufacturing processes in restoration, conservation, and historic preservation [9] and testing of materials available on the market [10]. In general, the potential applications of additive manufacturing processes in conservation and restoration lie primarily in the production of replicas, customized support structures and precisely fitting additions. Furthermore, 3D models and 3D printing can be used to produce design drawings for new workpieces that are to be integrated into a listed building and avoid faulty designs in advance. The aim of this study was to recreate an often-used weather-sensitive sandstone (“Bebertaler Sandstone”), which is hardly available anymore due to the closure of quarries, by additive manufacturing with a low calcium geopolymer fine mortar.

RESULT & DISCUSSION

For the development of the geopolymer fine mortar, it was necessary to determine the material properties of the Bebertaler sandstone beforehand. For this purpose, the compressive and flexural strength, the particle size, the capillary water absorption, and the bulk density were determined. In addition, the coloration in dry and wet condition was investigated. It plays a special role from the viewpoint of monument preservation, so that the developed geopolymer fine mortar should correspond to it as far as possible. Furthermore, the additive manufactured geopolymer fine mortar must be workable by stonemasons ’methods like grinding, cutting, and scraping. Table 1 shows the mechanical properties and bulk density of the Bebertaler sandstone as well the capillary water absorption. Due to the high capillary water absorption, frost damage occurs in historic structures made from this sandstone.

Table 1. Material parameters of the Bebertaler sandstone

Compressive Strength [MPa]	**Flexural Strength** [MPa]	**Bulk Density** [g/cm³]	**Water Absorption** [kg/m²·h^{0,5}]
81.6 ± 5.5	7.8 ± 0.8	2.4	1.6

For the development of the geopolymer fine mortar, a metakaolin from NEWCHEM GmbH (Austria) was used. The metakaolin was characterized in terms of its chemical and mineralogical composition by ICP-OES and XRD analysis. In addition, the pozzolanic reactivity was characterized with the modified Chapelle-test described in the French norm NF P 18-513, Annexe A and the particle size measured by laser granulometry. The determined material properties of the used metakaolin are given in table 2.

Table 2. Material parameters of the used metakaolin

SiO_2 [%]	**Al_2O_3** [%]	**TiO_2** [%]	**K_2O** [%]	**Si/Al** [-]	**Amorphous content** [%]	**Kaolinite** [%]	**Quartz** [%]	**Reactivity** [mg/g]	**Particle Size d_{10}; d_{50}; d_{90}** [µm]
52.1	47.3	0.47	0.49	1:1	71.7	24	2.5	1275	0.75; 8.2; 20.2

A sodium silicate solution made by Woellner GmbH (Germany) was used as an alkaline activator. The SiO_2/Na_2O ratio of the solution was adjusted to 1.6 by adding NaOH pellets. Due to the high shrinkage of the geopolymer binder of 5.2 mm/m, a granite based crushed sand was used as a filler for mortar preparation to decrease the shrinkage to 0.7 mm/m. A low amount of iron pigment was added to achieve the coloration of the Bebertaler sandstone. The composition of the geopolymer fine mortar used for additive manufacturing is shown in table 1.

Table 3. Composition of the geopolymer fine mortar for additive manufacturing to replicate natural sandstones

Sodium silicate solution (Module 1.6)	**Metakaolin**	**Granite based crushed sand** (particle size 0 – 0.5 mm)	**Water**	**Fe_2O_3 pigment content** based on the solids content
18.7 %	20.6 %	58.8 %	4.5 %	0.1 %

The developed geopolymer fine mortar exhibits rheological properties suitable for 3D printing in that it liquefies when force is applied and exhibits a stable and resilient base structure when no force is applied. It is also characterized by the fact that no organic additives are required to adjust the consistency. Solidification of the geopolymer fine mortar starts after approx. 5 h at 20 °C and can be significantly accelerated by moderate thermal treatment of 60 °C to 30 min. The project partner WZR ceramic solutions GmbH (Germany) developed a special dual-purpose mixing-extruder for this material and started by printing prismatic samples with dimensions of 50 × 70 × 200 mm. The printed specimens exhibited a compressive strength of approx. 80 MPa and a flexural tensile strength of approx. 13 MPa, so that comparable mechanical properties to the Bebertaler sandstone were achieved. Climate change storage tests and eluate investigations showed that the developed geopolymer fine mortar has a high durability. The last objective of this study was the creation of an additive manufactured sandstone replica of a complex shaped sandstone specimen which should be reworked in a stonemasonry way with only a small effort. Figure 1 shows the shape of the sandstone to be replicated as a CAD model (left), extrusion printing of the replica with the geopolymer fine mortar (middle), and the demonstrator component with one half reworked in a stonemasonry manner (right).

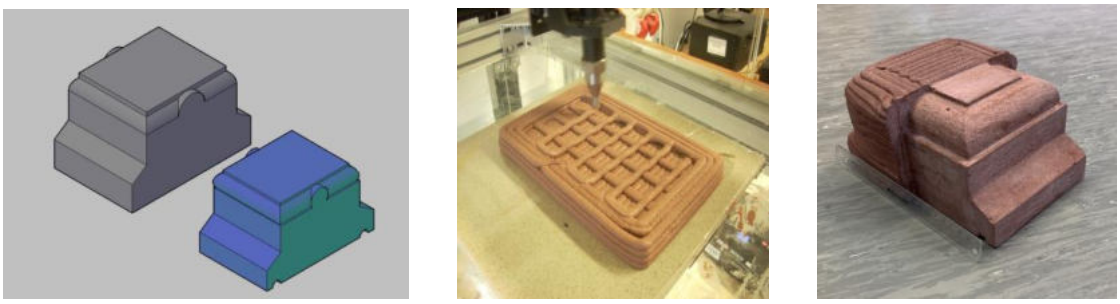

Figure 1. CAD-Model (left), 3D-printing of geopolymer fine mortar (middle) and demonstrator of the replicate sandstone (right)

CONCLUSION

The aim of this study was to recreate an often-used weather-sensitive sandstone ("Bebertaler Sandstone"), which is hardly available anymore due to the closure of quarries, by additive manufacturing with a geopolymer fine mortar. The developed geopolymer fine mortar showed excellent rheological properties for additive manufacturing and high durability especially under different climate conditions.

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